

# **Storm-scale Radar Data Assimilation with EnKF at Penn State: Successes and Issues**

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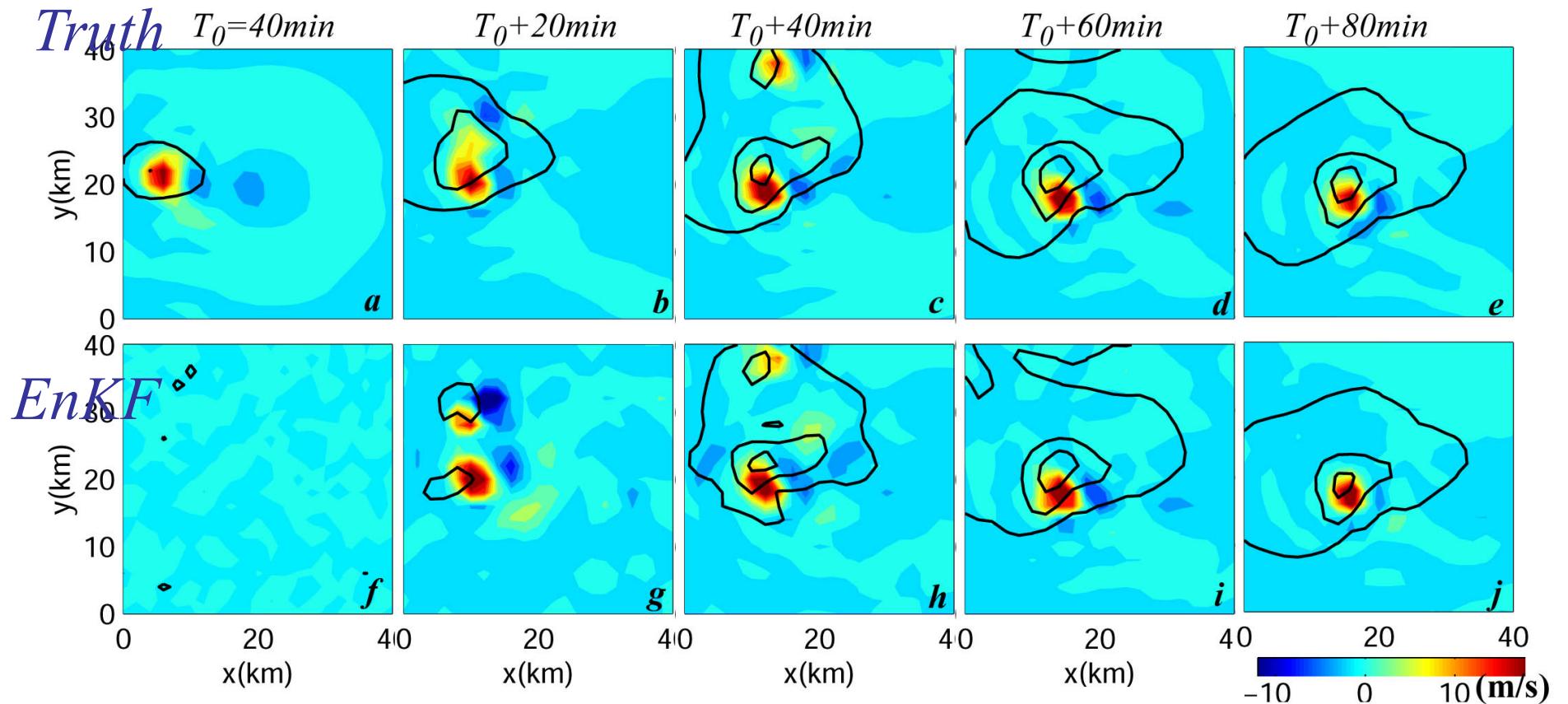
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# First Test of EnKF for Limited-area Models: Assimilation of Radar Observations of Supercells

(Snyder and Zhang 2003; Zhang, Snyder and Sun 2004; Dowell et al. 2004; all in MWR)

Observations: radial velocity  $V_r$  only, available every 5 minutes where reflectivity  $dBZ > 12$

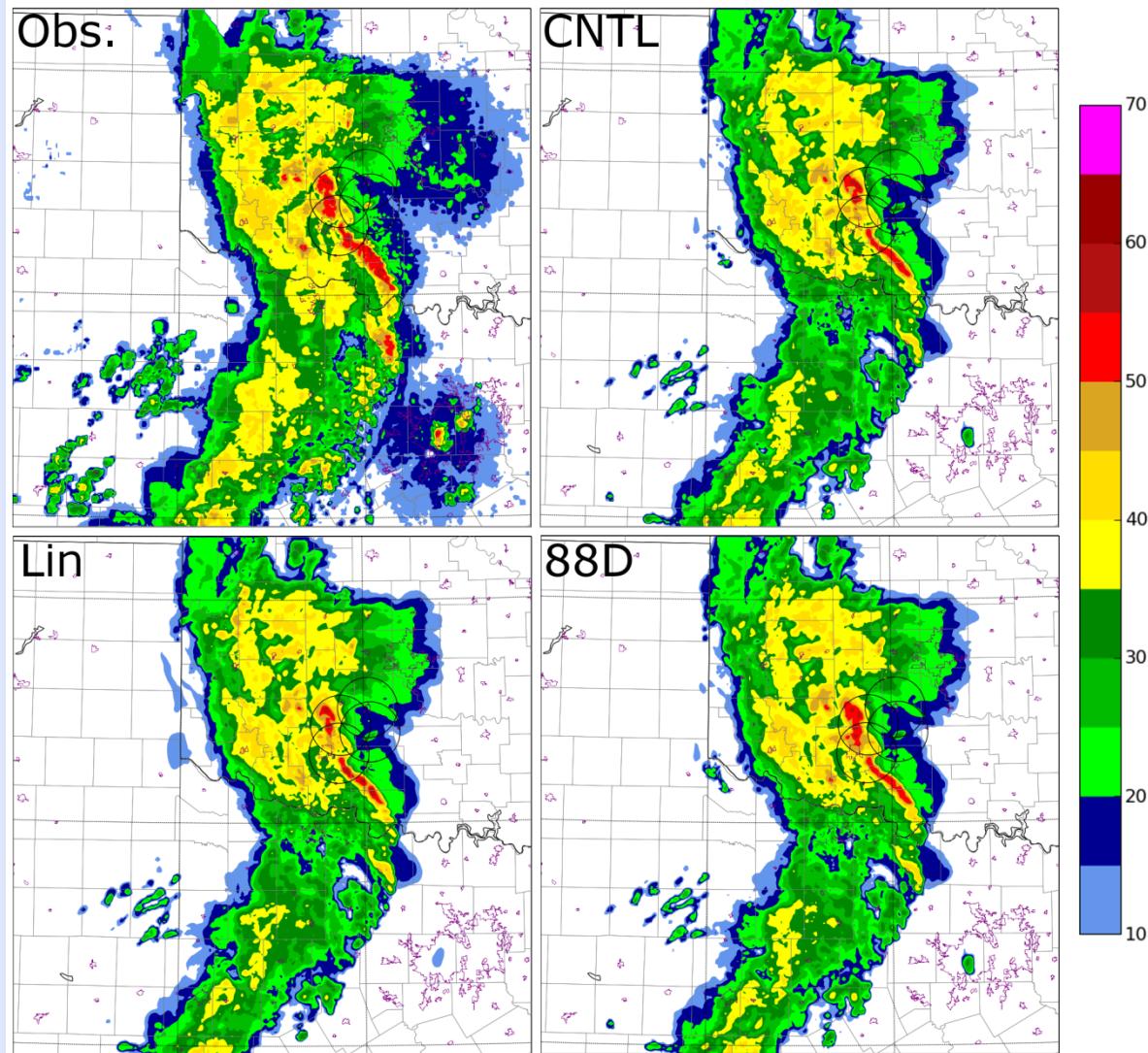
Vertical velocity at 5km (colored) and surface cold pool (black lines, every 2K)



# Multi-scale/Multi-radar EnKF Success at OU

## Assimilating 88D vs. CASA radar obs

Courtesy of Nathan Snook, Ming Xue & Y. Jun



- Main convective line and trailing stratiform region well represented.
- Cells in SW portion of domain too weak in the models.
- Models underestimated intensity of small individual cells ahead of the convective line.

Also see Lou Wicker and Jim Marquis's talks later

Some issues raised in  
Zhang et al 2004 remain:

- (1) Bad initial guess
- (2) Data coverage
- (3) Lack of BL obs

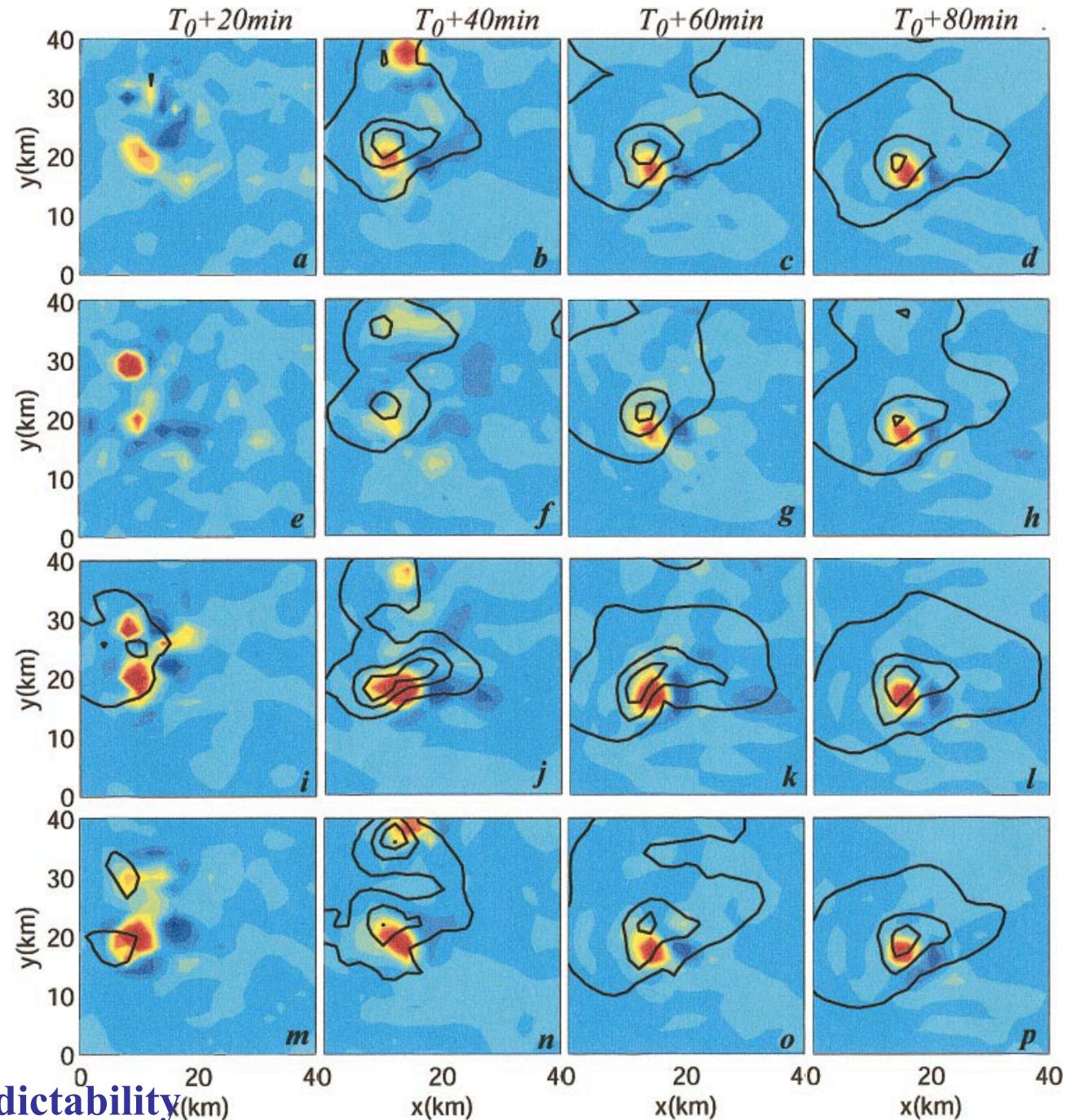
Some may be dealt with  
the use of dBZ and/or  
cloud analysis (CAPS)

Other issues emerge:

Model error, especially  
in microphysics:  
Storm-scale parameter  
estimation with real data

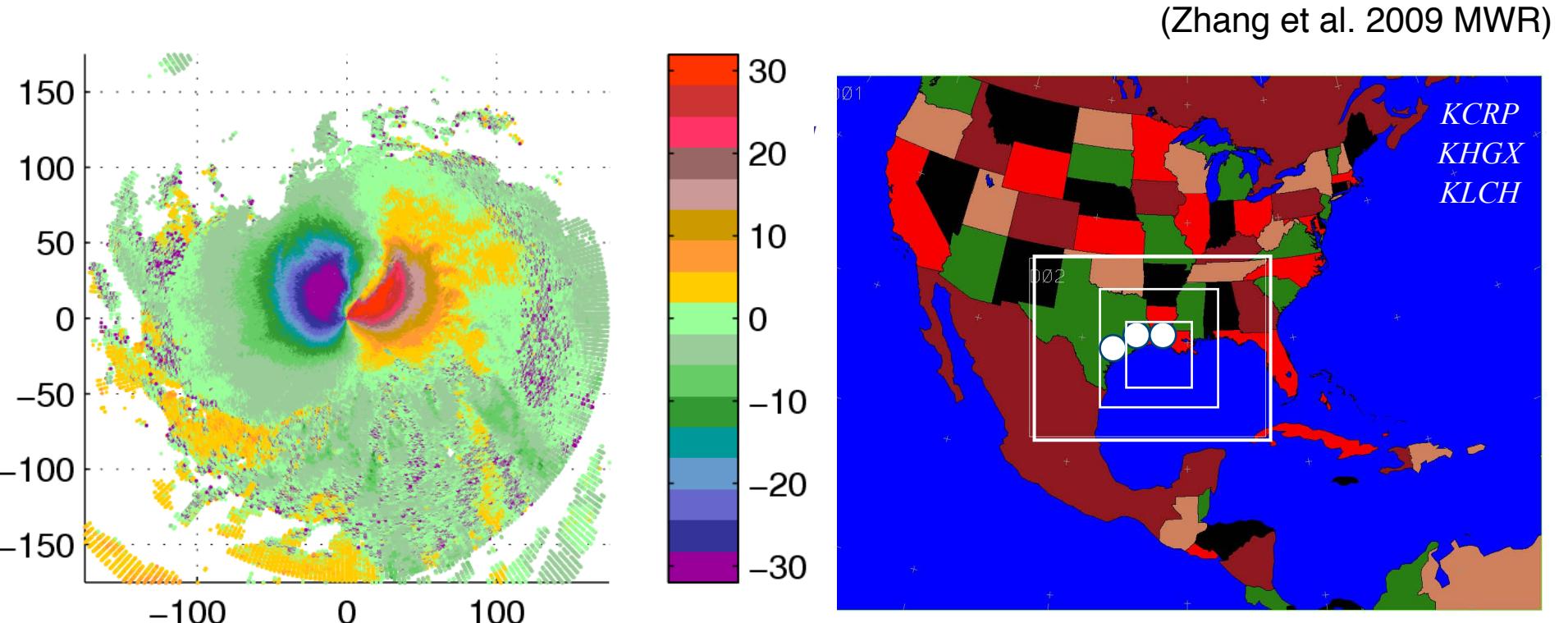
Multiscale covariance  
localization, inflation

IC/BC, lead time and predictability

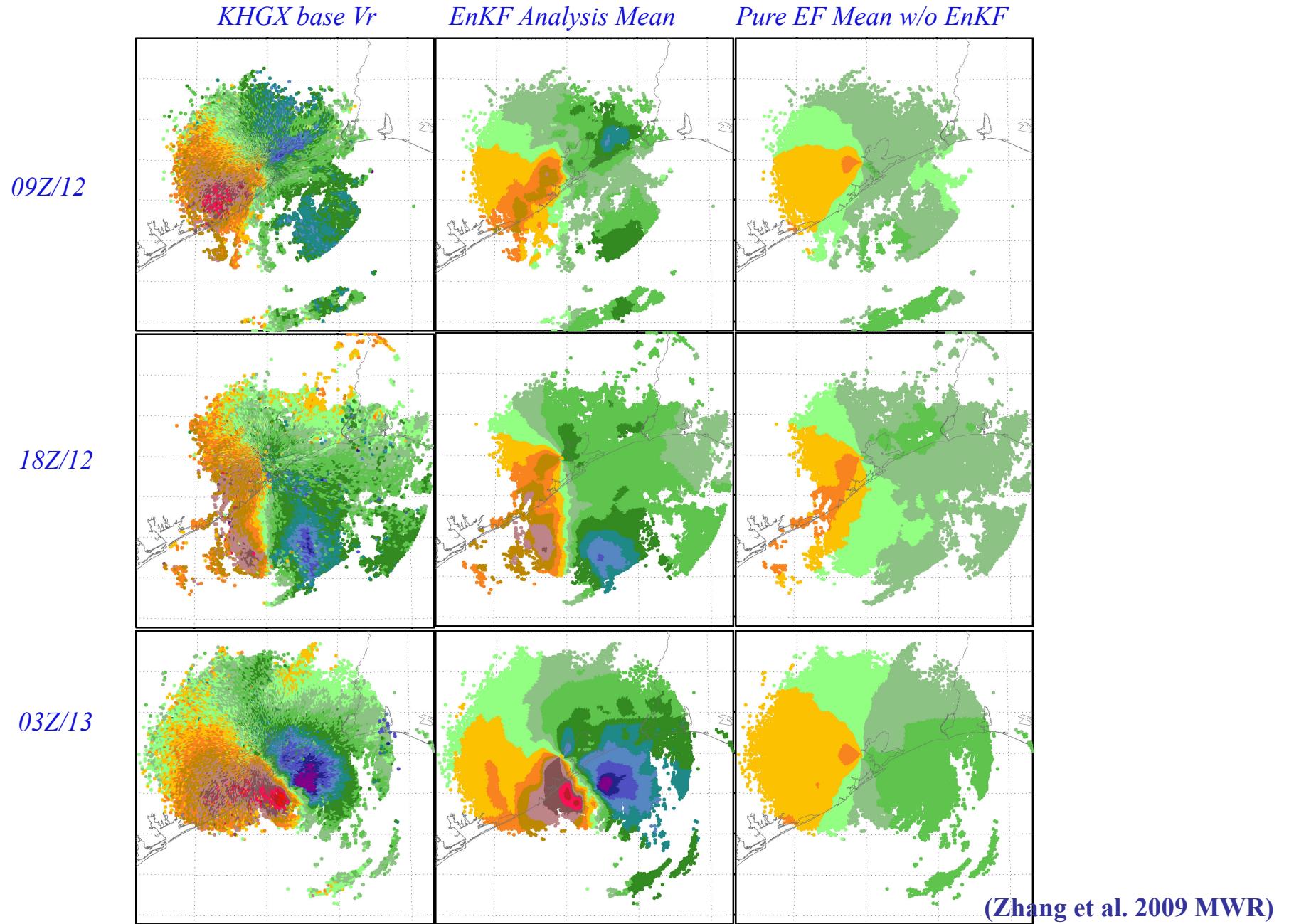


# EnKF: Assimilate WSR88D Vr Winds for Hurricanes

- **Model:** Weather Research and Forecast Model (WRF) with 4 domains two-way nested and grid sizes of 40.5, 13.5, 4.5, and 1.5km [NOAA HWRF: model 9km]
- **Data:** Doppler winds from three coastal weather surveillance radars [available routinely for more than 20 years but never used in any NOAA operational models]
- **Data assimilation method:** Ensemble Kalman Filter (EnKF) with 30 members [as we will show, the current scheme in NOAA operational models is insufficient]

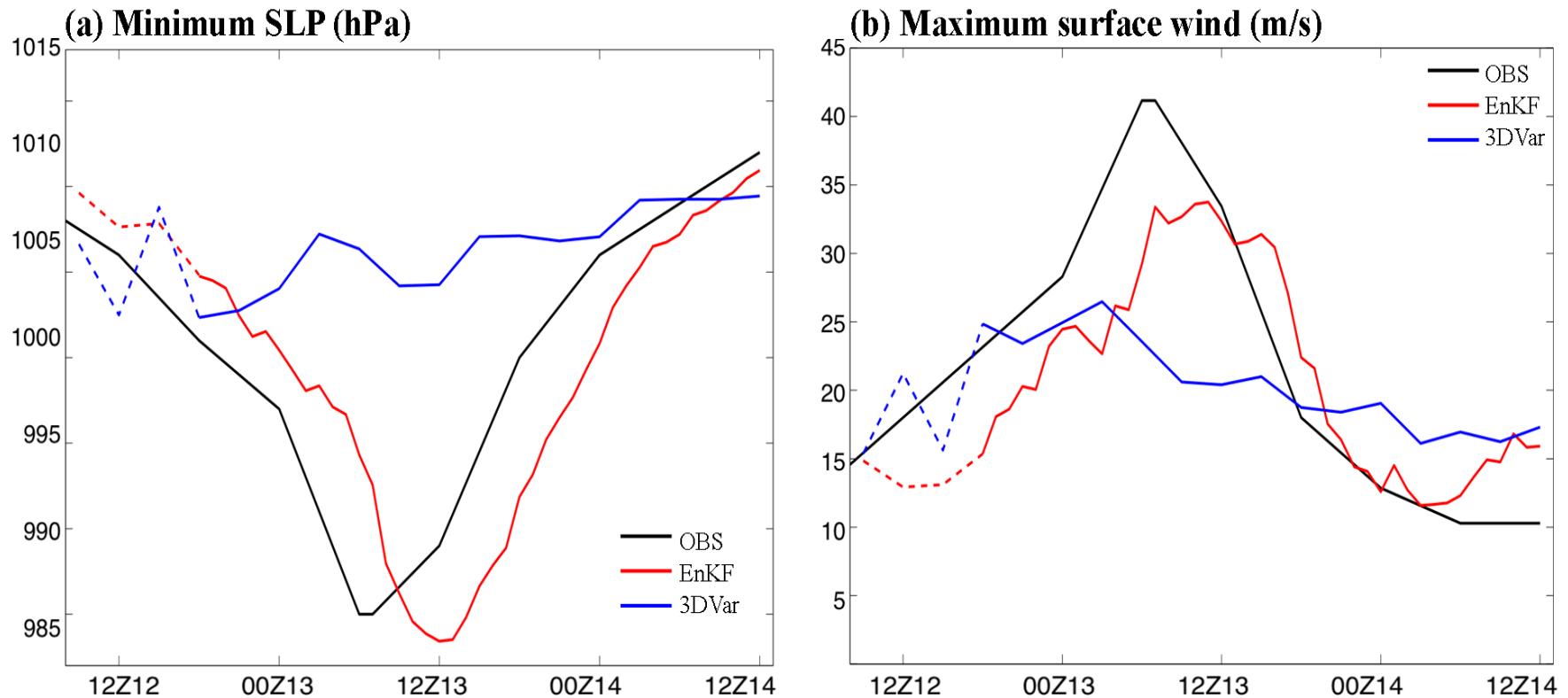


# *EnKF Analysis vs. KHGX Obs vs. NoDA*



# Assimilate W88D Doppler Vr for Humberto'05

*WRF/EnKF Forecast vs. Observations vs. 3DVAR*

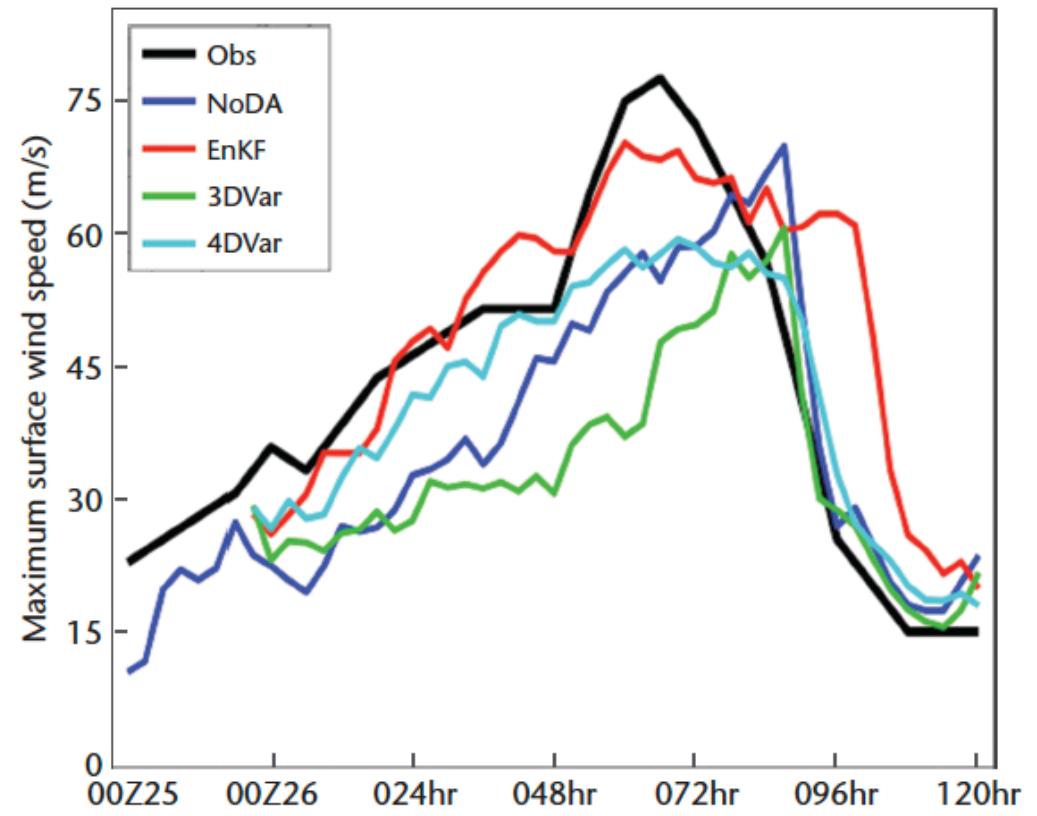
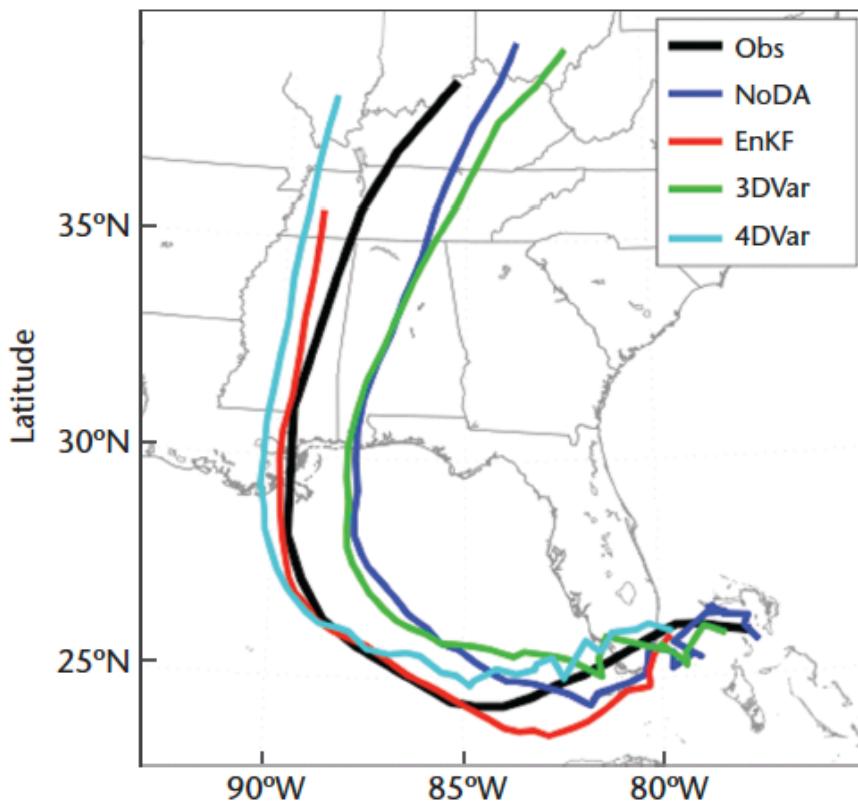


The WRF/3DVAR (as a surrogate of operational algorithm) assimilates the same radar data but without flow-dependent background error covariance, its forecast failed to develop the storm despite fit to the best-track observation better initially

(Zhang et al. 2009 MWR)

# Katrina (2005): WRF/EnKF assimilating 88D Vr obs

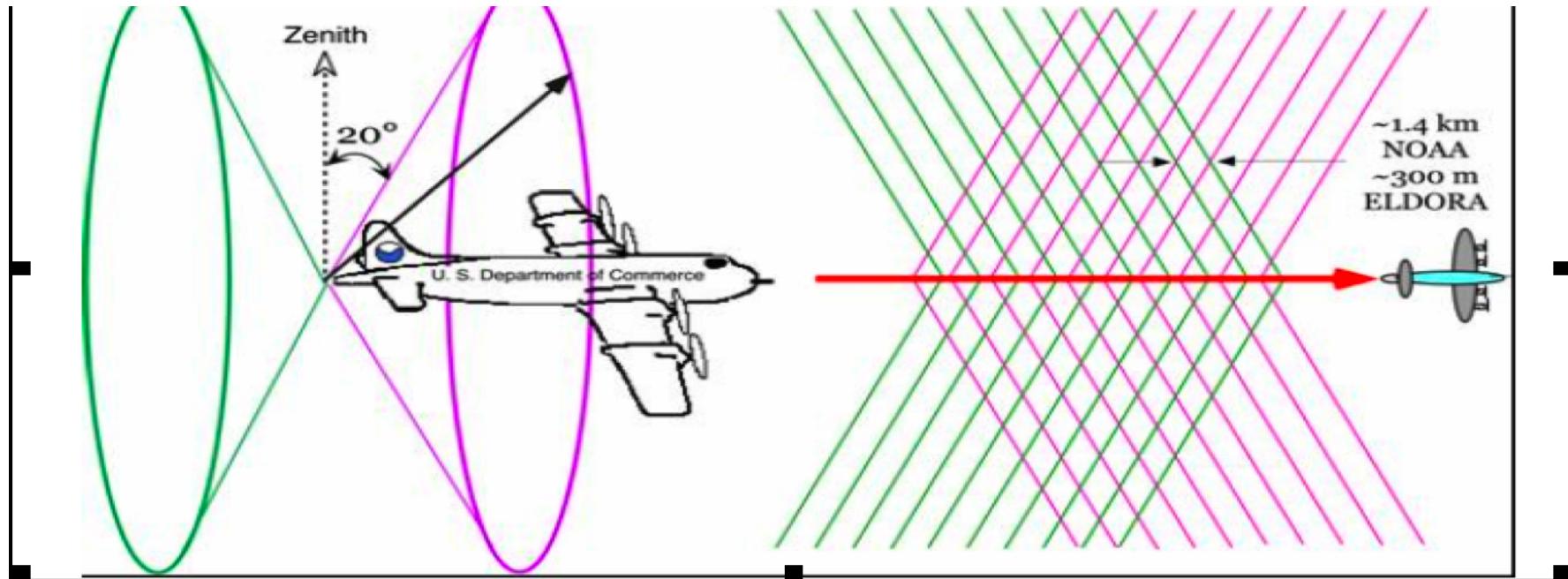
In comparison with 3DVAR and 4DVAR  
(Weng, Zhang and Zhang 2011 CiSE)



Notes: KAMX 88D Vr Radar at 1430, 1530, 1630, 1730, 1900, and 2000 UTC 25 Aug 2005, same as the P3 obs times shown next; 4DVAR uses  $Dx=13.5\text{km}$  the analysis due to computing cost )

# Assimilating Airborne Doppler Radar Winds

*Available for 20+ years but never used in operational models due to the lack of resolution and/or the lack of efficient data assimilation methods*



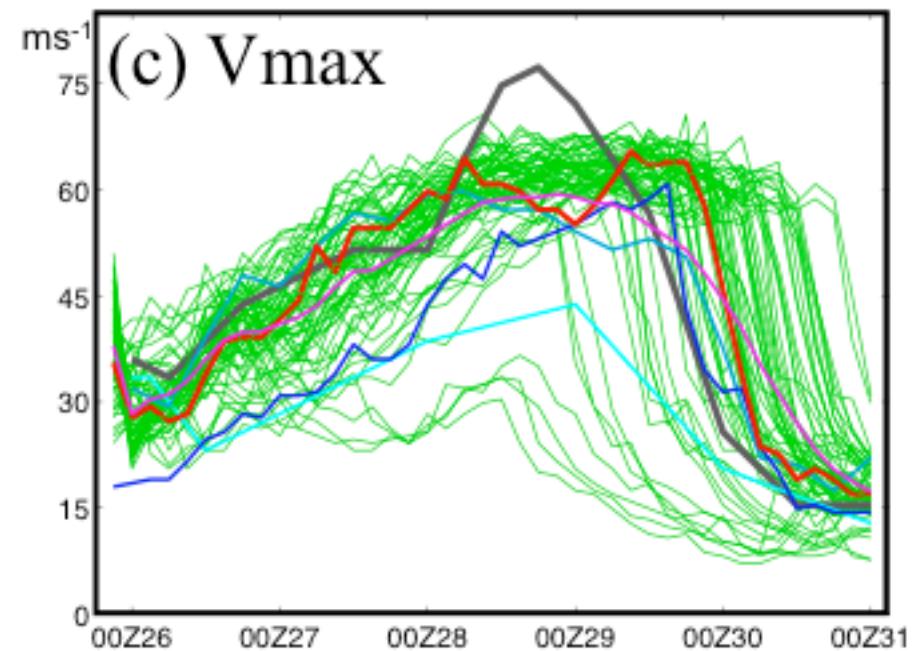
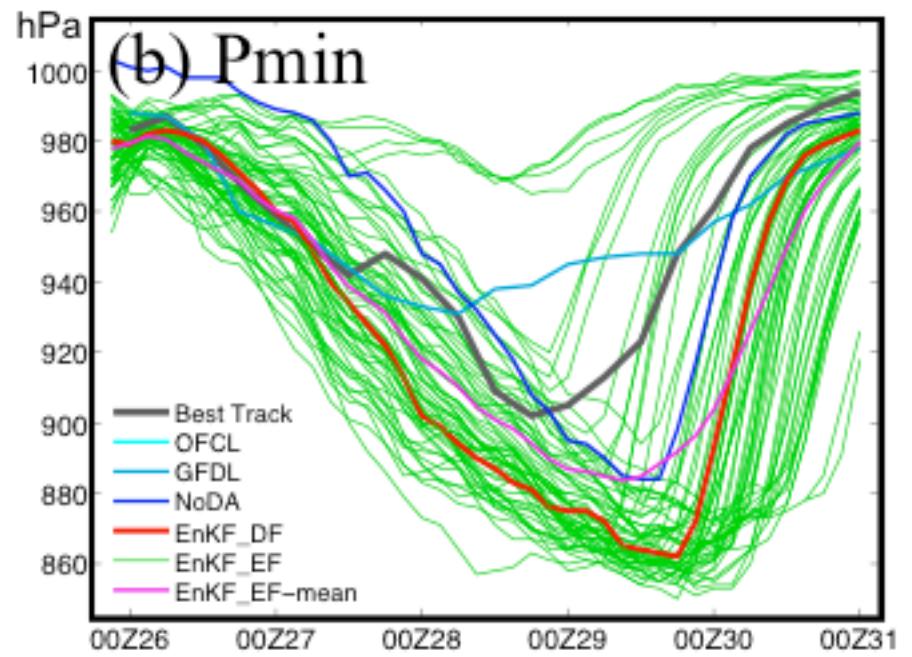
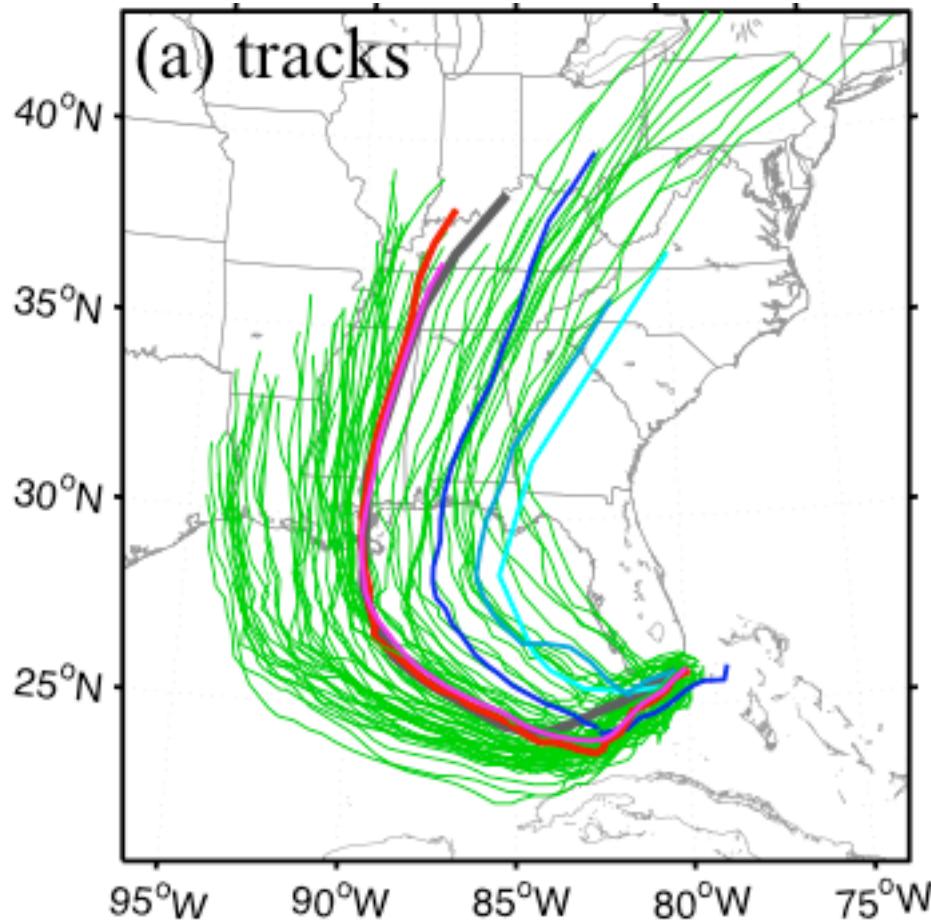
SOs: 1. Separate forward and backward scans; 2. removing data with vertical pointing angles greater than 45 degree; 3. treat every 3 adjacent full scans as one fixed-space radar (translation<5km); 4. thinning ---one bin for 5 km in radial distance and 5 degree in scanning angle; 5. use medium as SO after several additional QC criteria checking

*These SOs are generated on flight of NOAA P3's; transmitted to ground in realtime*

# WRF/EnKF Performance With airborne Vr obs

(Weng and Zhang 2011, MWR)

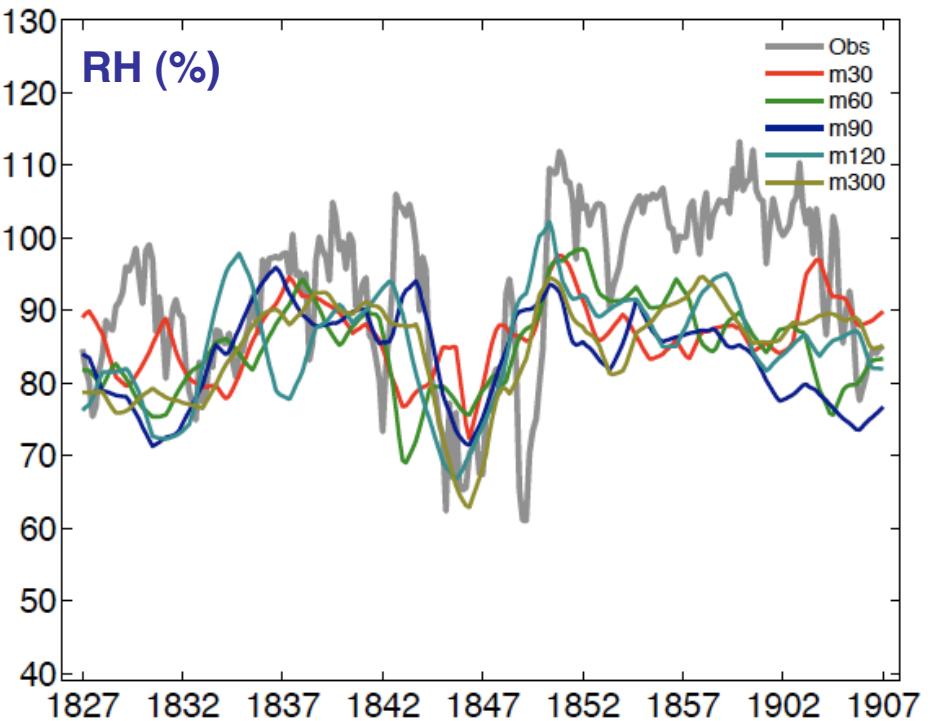
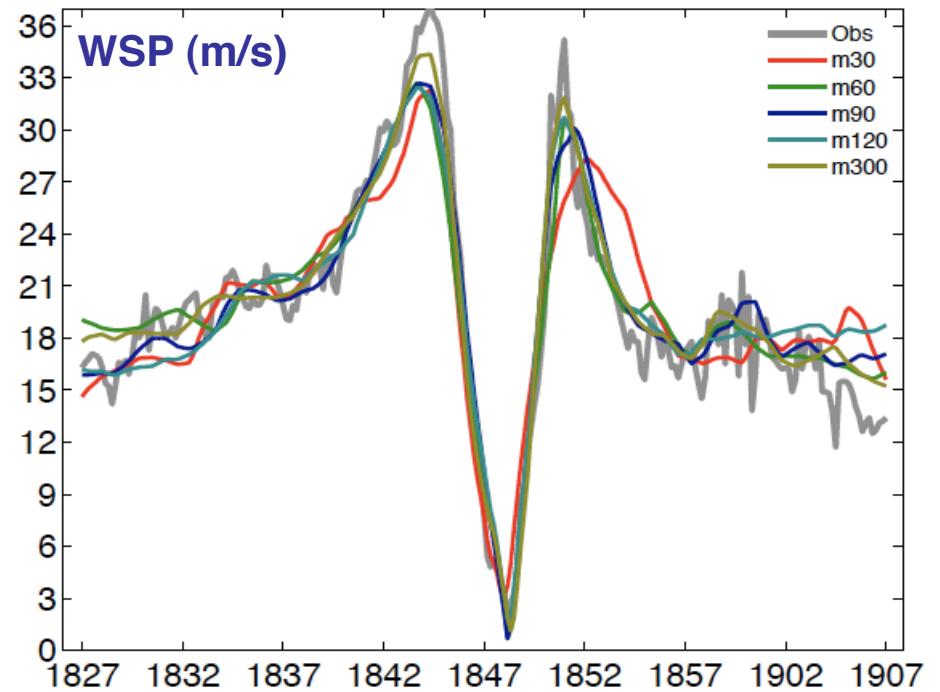
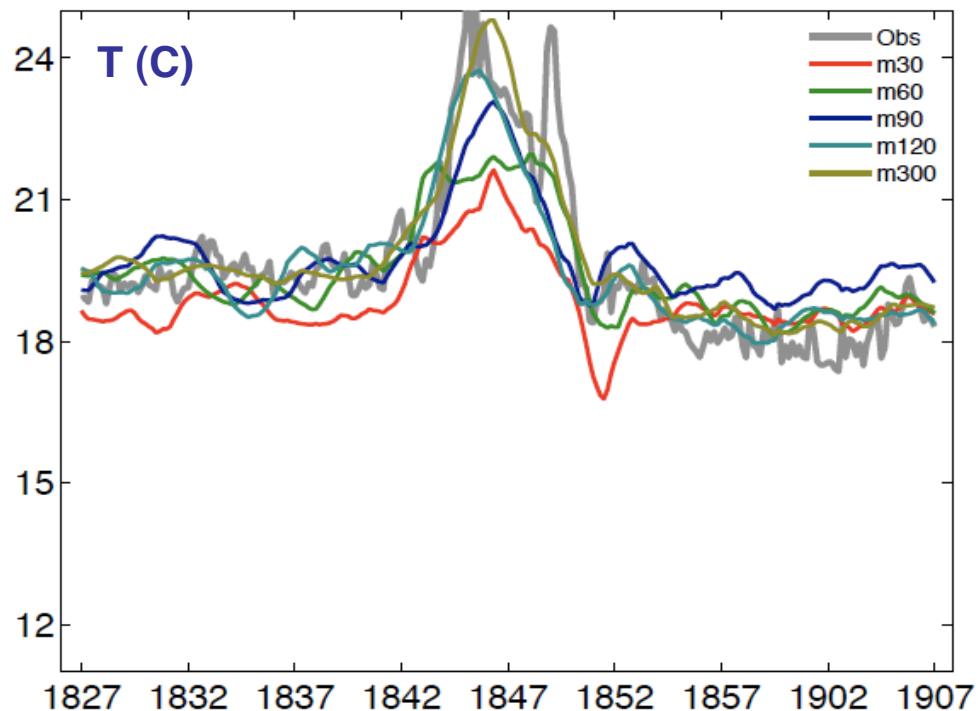
*60-member ensemble forecast  
from EnKF posterior uncertainty*



# Verification of flight-level wind, T and RH (leg 5)

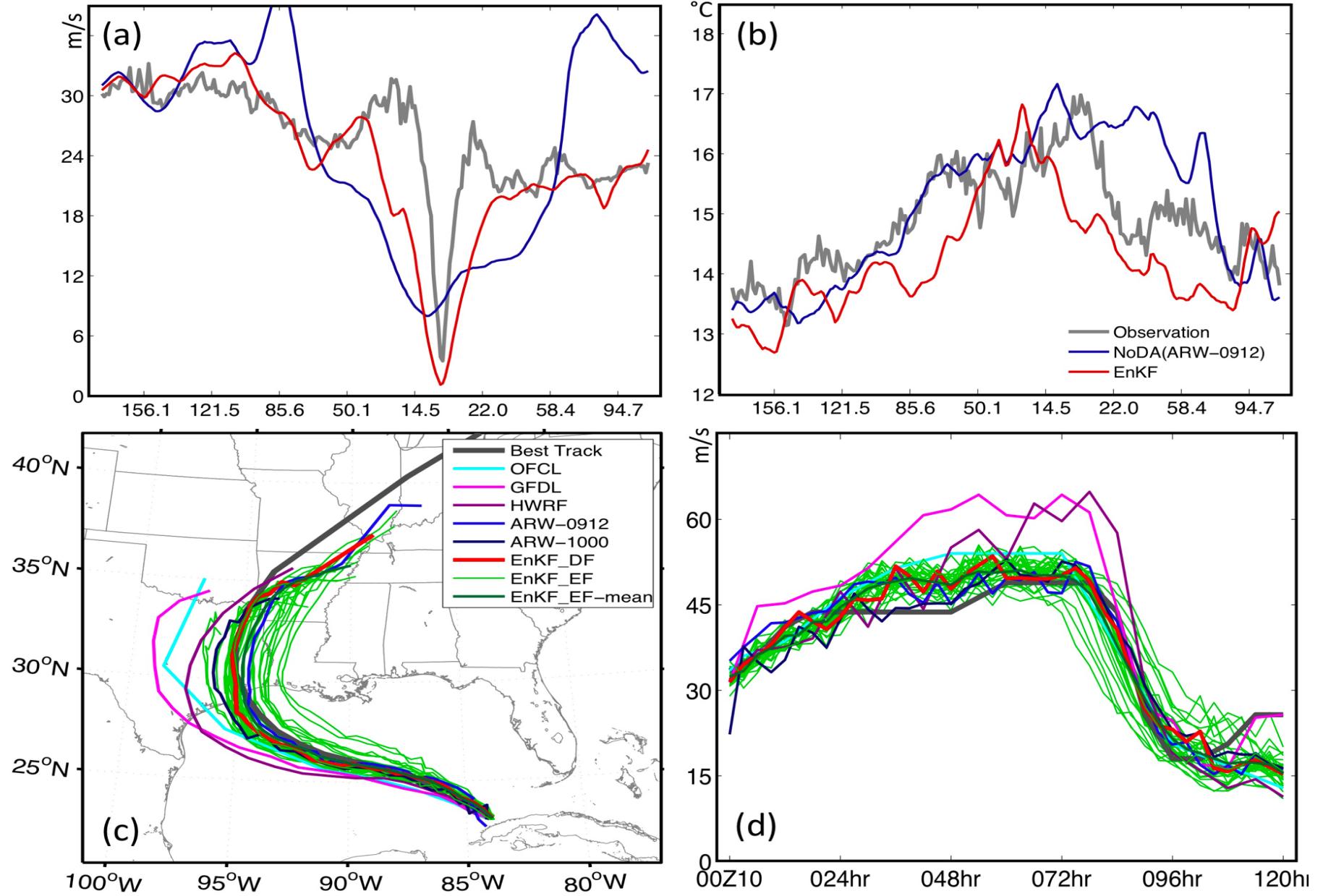
*Sensitivity to ensemble size:  
30 good, >=60 even better*

(Weng and Zhang 2011)



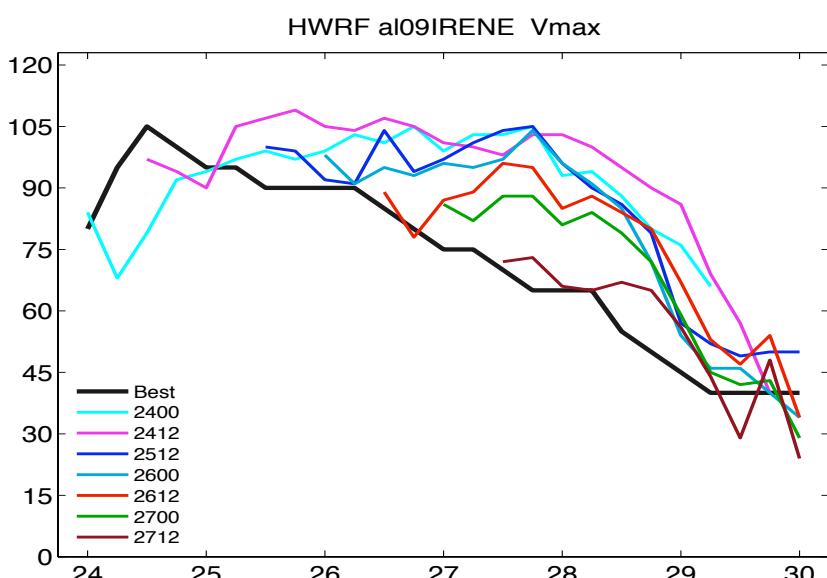
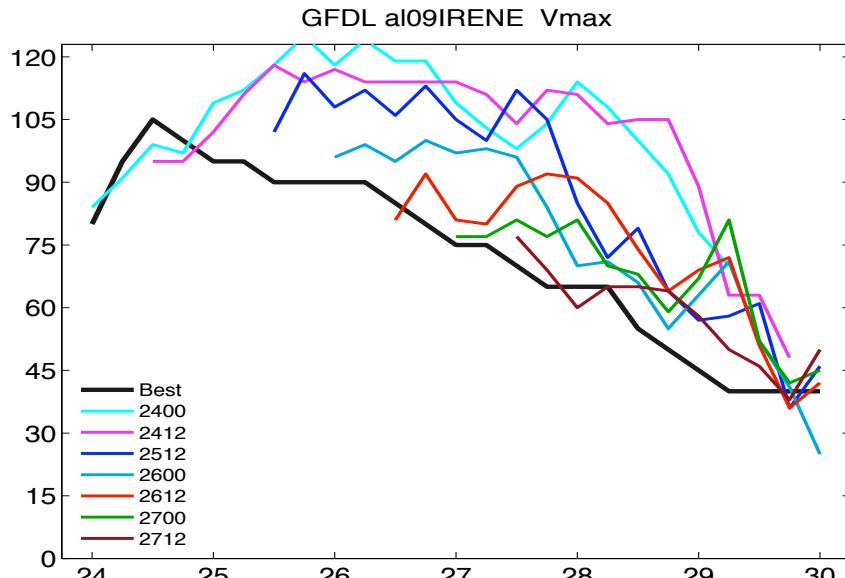
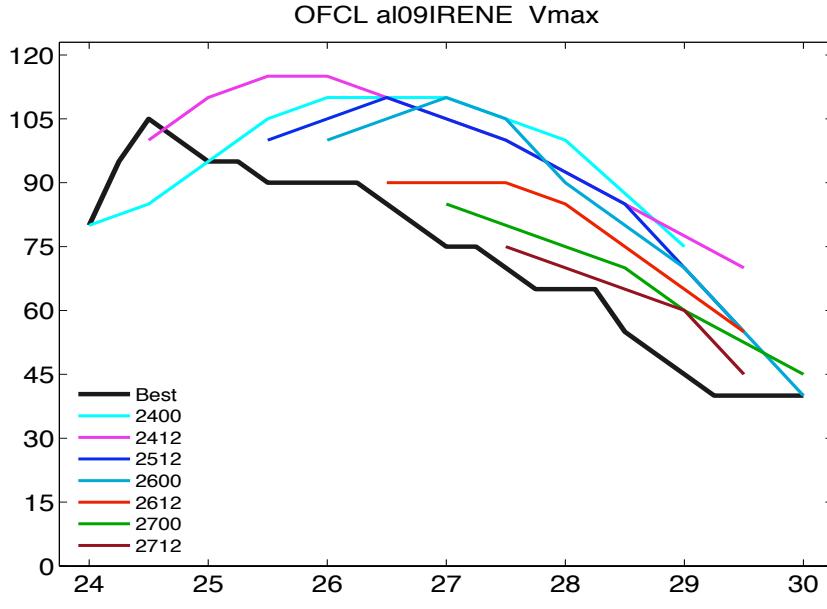
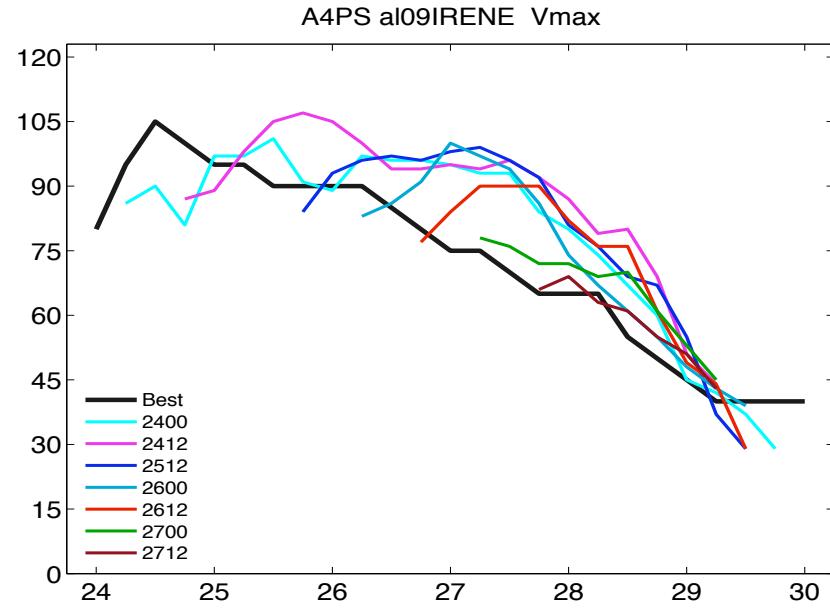
# Hurricane IKE (2008): Forecast from 00Z 10 Sept

## *Realtime EnKF assimilation of airborne Doppler winds*



# Irene (2011): HFIP Stream1.5 with WRF/EnKF

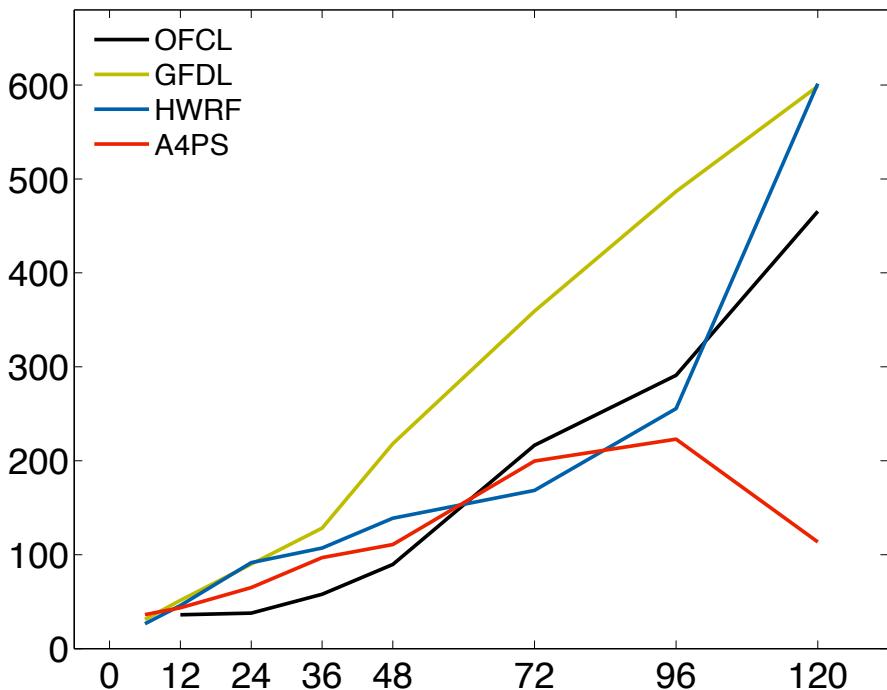
## *Realtime assimilation of airborne Vr obs (7 missions)*



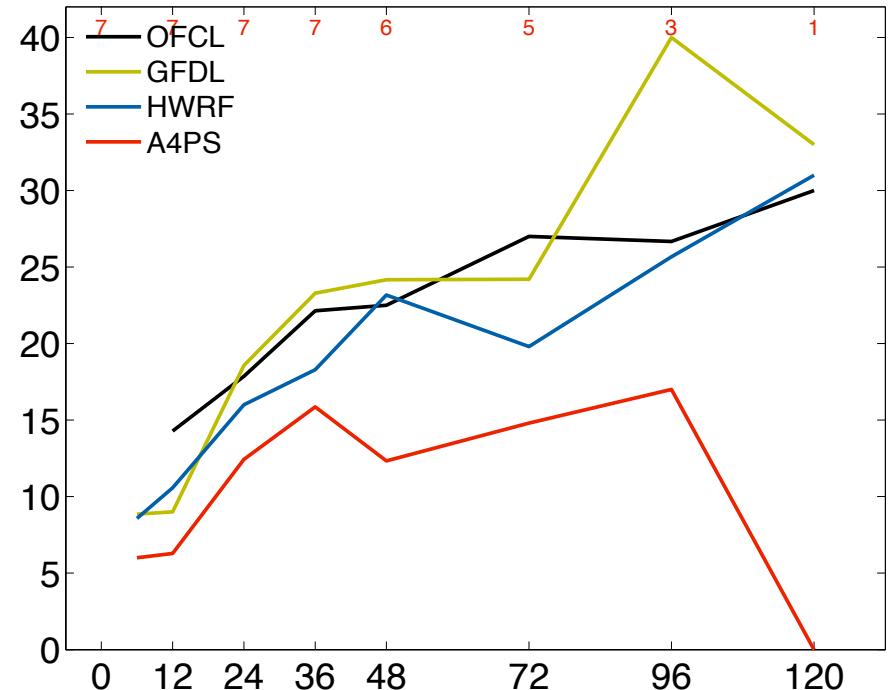
# EnKF Performance Assimilating Airborne Radar OBS

*Mean Absolute Error and Ensemble Spread for 7 missions of Irene (2011)*

ABS Error of position (km) for 2011–2011



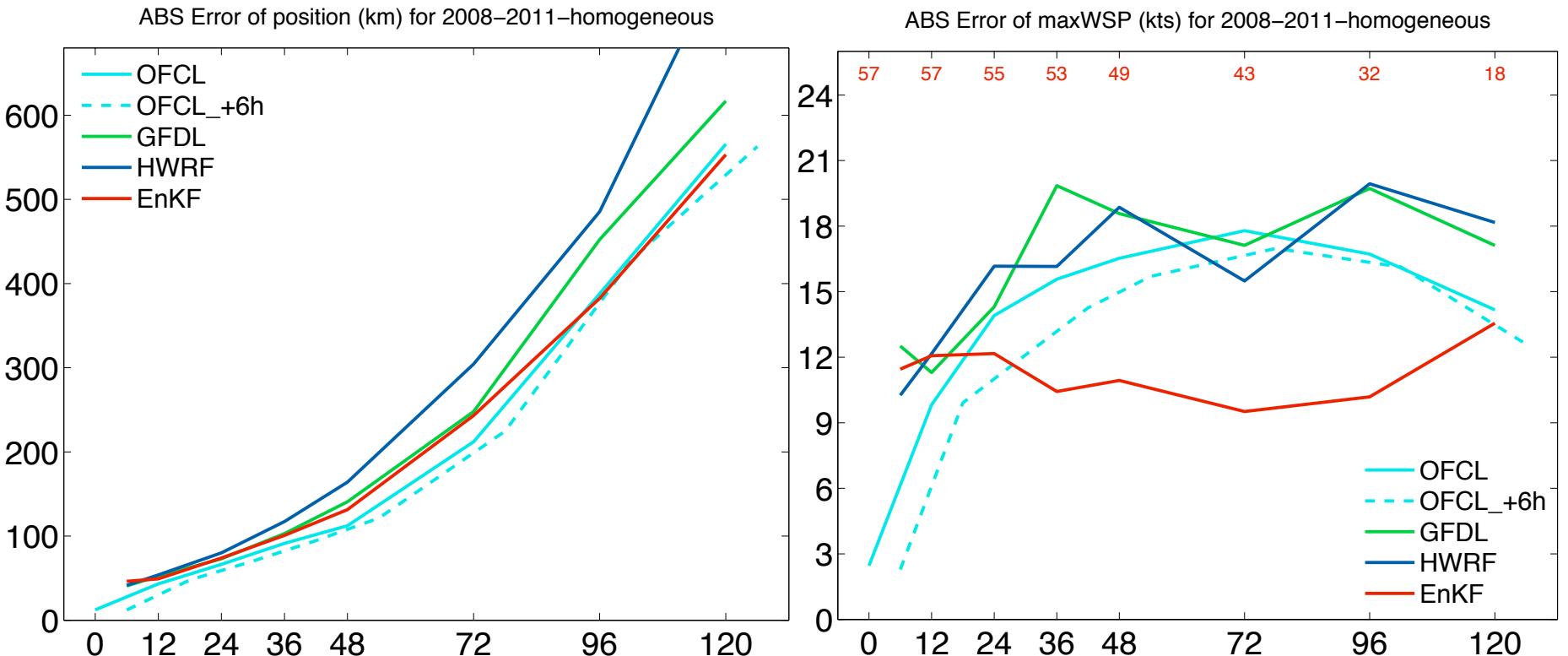
ABS Error of maxWSP (kts) for 2011–2011



A4PS: PSU 4.5km single forecast initialized with EnKF analyses

# EnKF Performance Assimilating Airborne Radar OBS

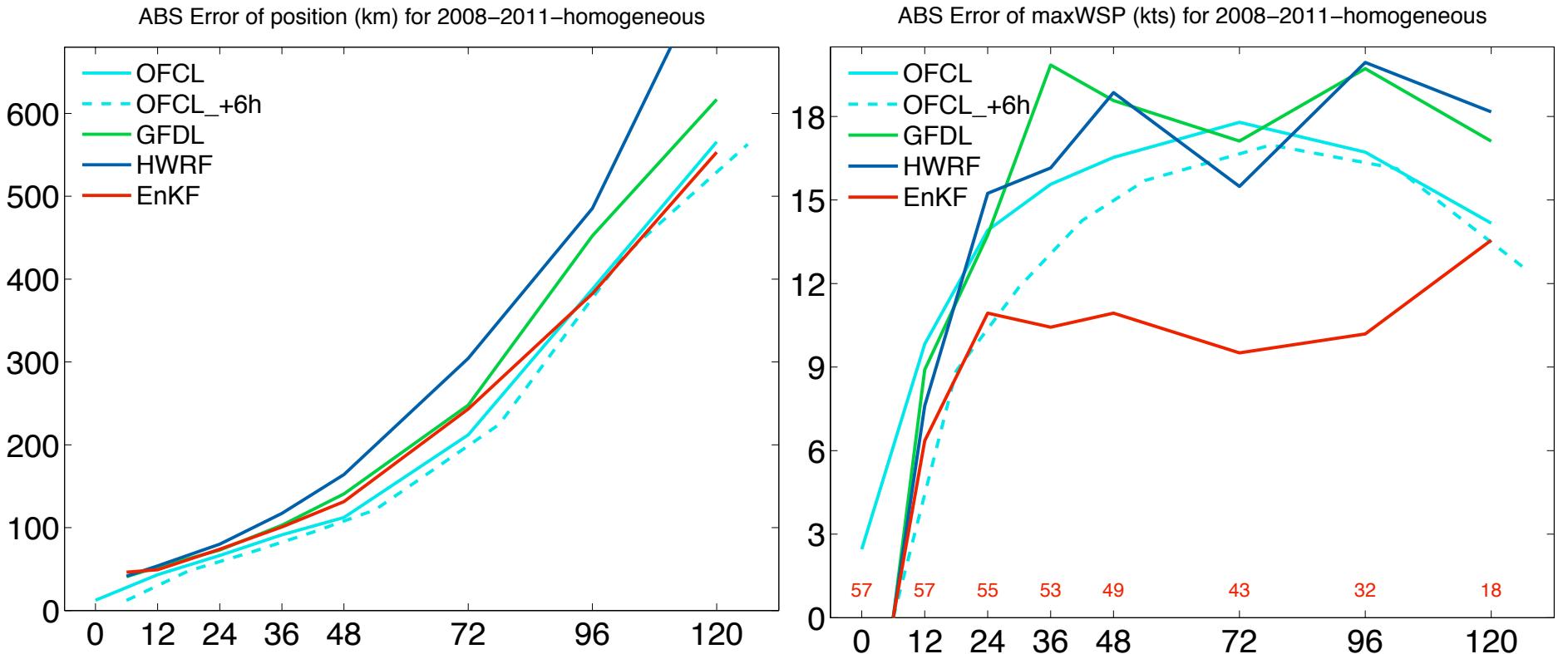
*Mean Absolute Error and Ensemble Spread for 66 missions during 2008-2011*



A4PS: PSU 4.5km single forecast initialized with EnKF analyses

# EnKF Performance Assimilating Airborne Radar OBS

*Mean Absolute Error and Ensemble Spread for 66 missions during 2008–2011*



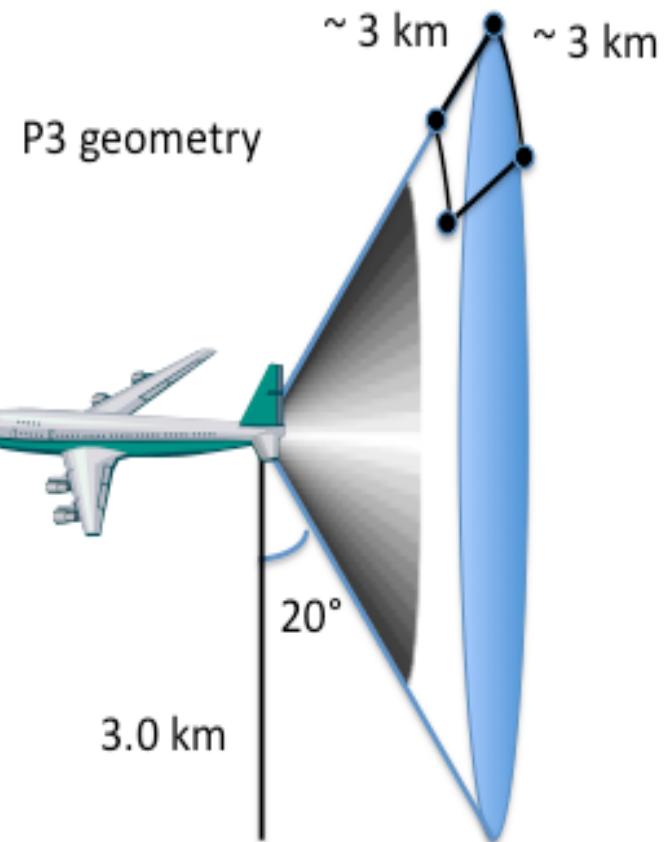
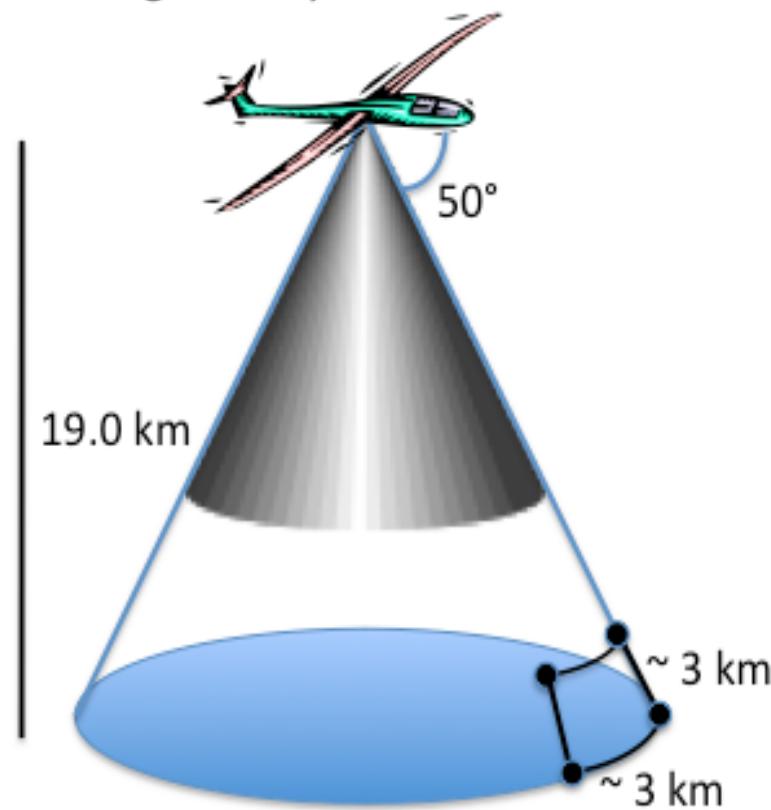
With bias correction of intensity error

$$\text{Corrected WSP} = \text{WSP} - \left( \frac{30\text{h} - t}{30\text{h}} \times \text{Bias\_at\_initial\_time} \right)$$

# HIWRAP Doppler Radar Vr from Global Hawk

NASA Hurricane and Severe Storm Sentinel (HS3)

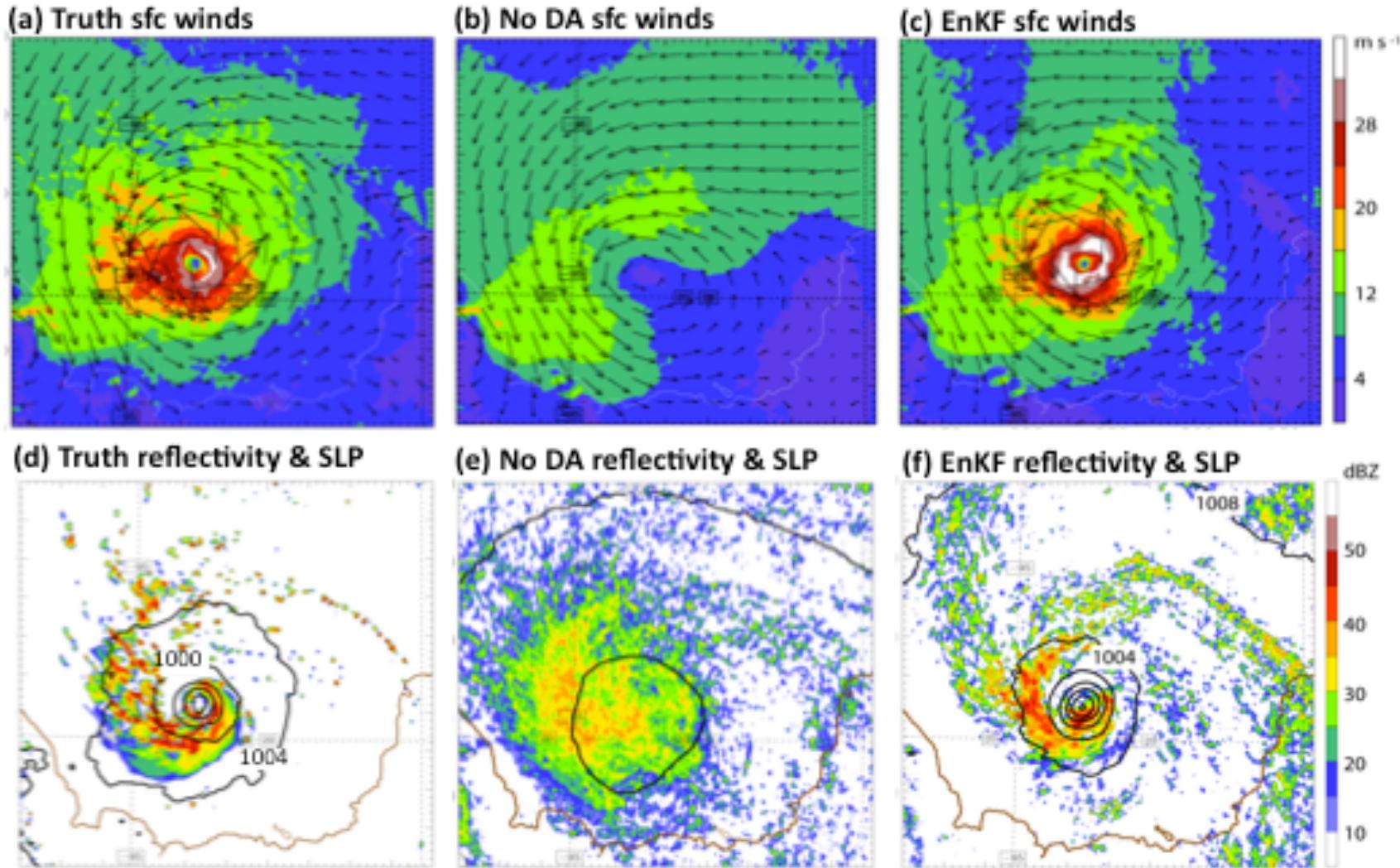
HIWRAP geometry



Courtesy of Jason Sippel and Scott Braun at NASA/GSFC

# Assimilating HIWRAP Vr from GH: OSSE

## NASA Hurricane and Severe Storm Sentinel (HS3)



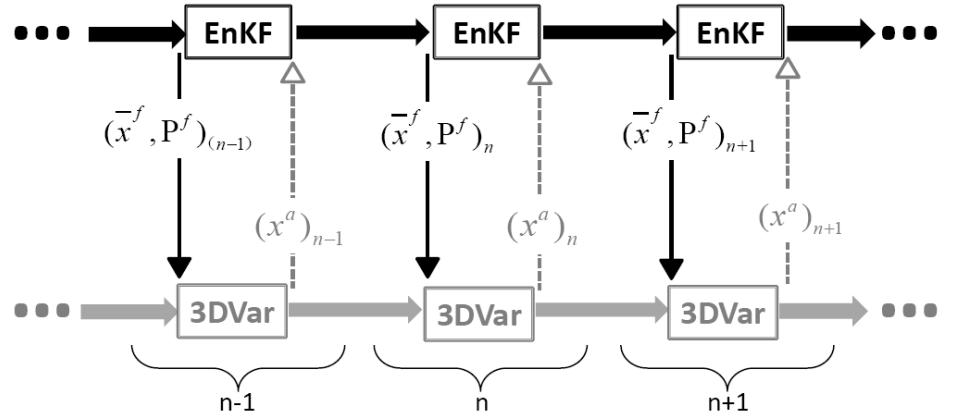
Courtesy of Jason Sippel and Scott Braun at NASA/GSFC

# Coupling EnKF with WRF 3DVar/4DVar

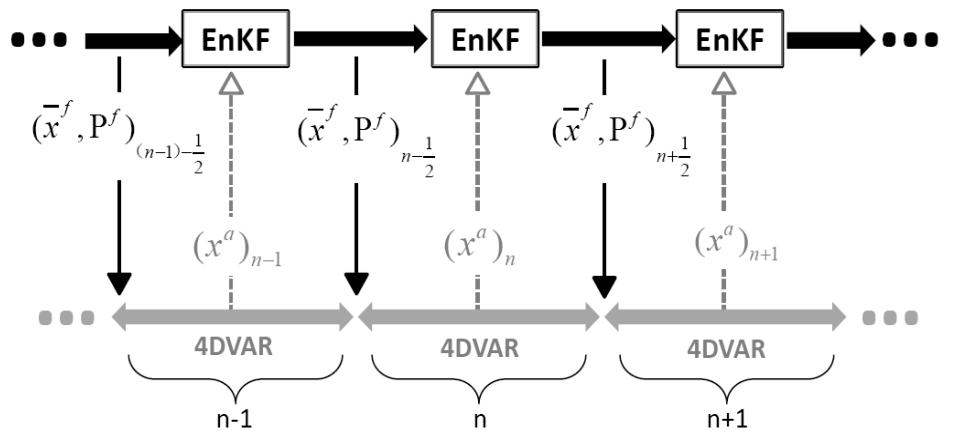
## Necessary Variable Changes:

- i) EnKF provides ensemble-based background error covariance ( $P^f$ ) for 3D/4DVar
- ii) EnKF provides the prior ensemble mean ( $\bar{x}^f$ ) as the first guess for 3D/4DVar
- iii) 3D/4DVar provides deterministic analysis ( $\bar{x}^a$ ) to replace the posterior ensemble mean for the next ensemble forecast

## Coupler of EnKF-3DVar Hybrid (E3DVar):



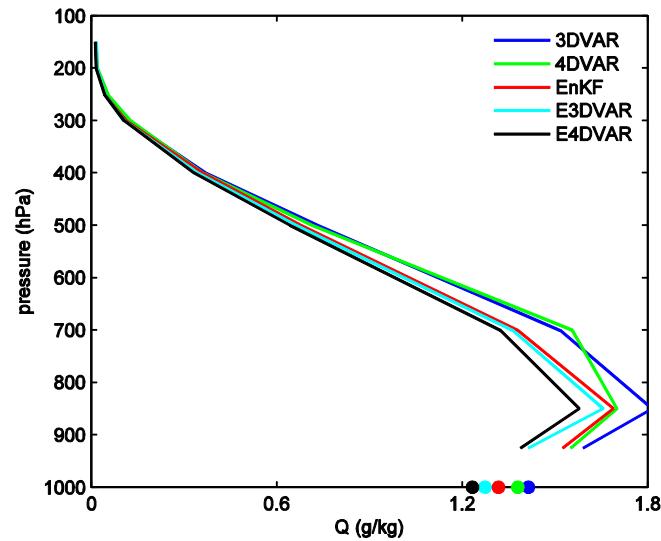
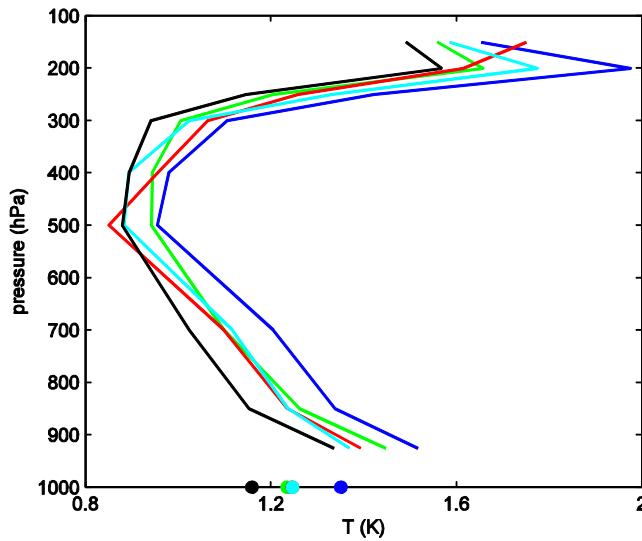
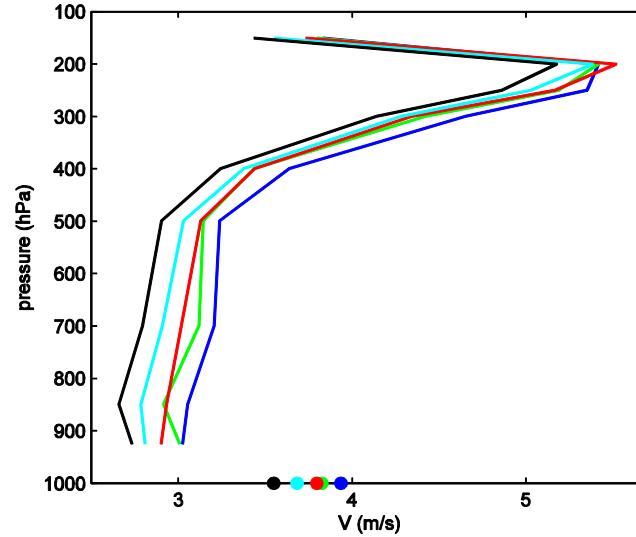
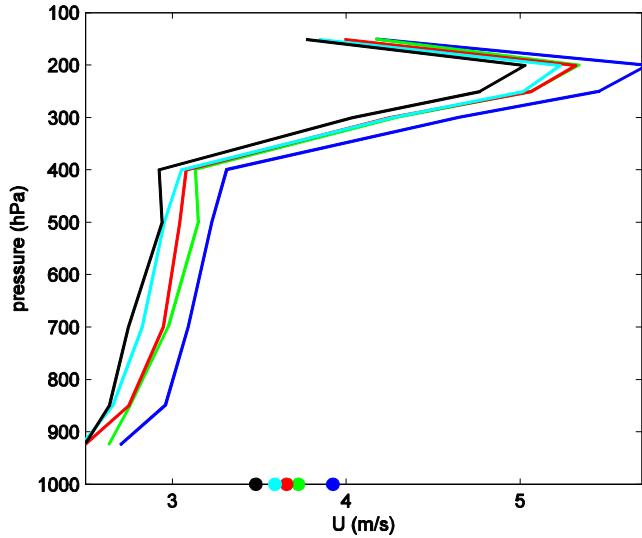
## Coupler of EnKF-4DVar Hybrid (E4DVar):



(Zhang and Zhang 2011; Zhang et al. 2009)

# *Comparison of 3DVar, 4DVar, EnKF, E3DVar & E4DVar*

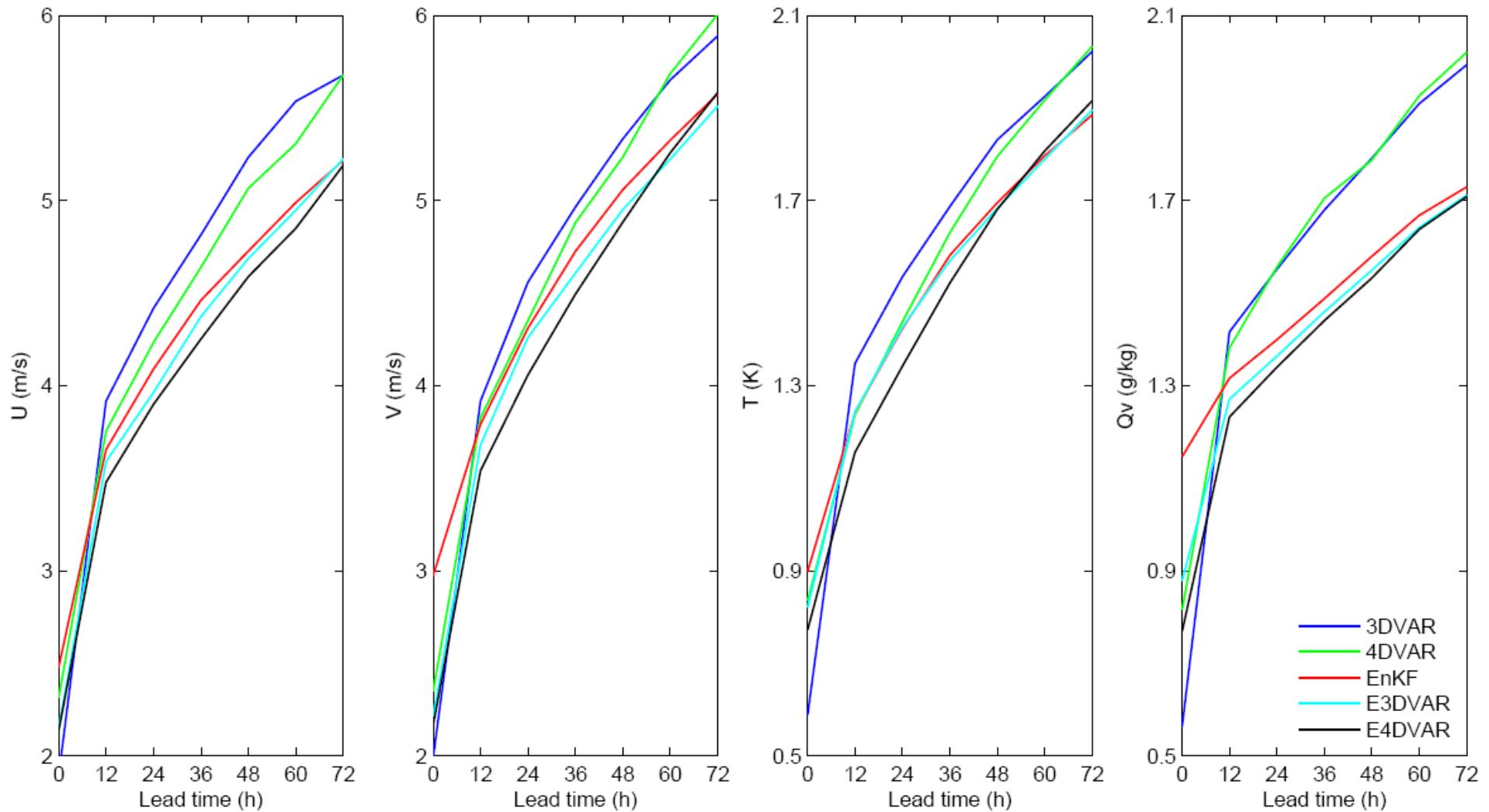
*Mean vertical profiles of month-averaged 12-h forecast RMSE*



(*Zhang et al. 2010; Zhang and Zhang 2011*)

# *Comparison of 3DVar, 4DVar, EnKF, E3DVar & E4DVar*

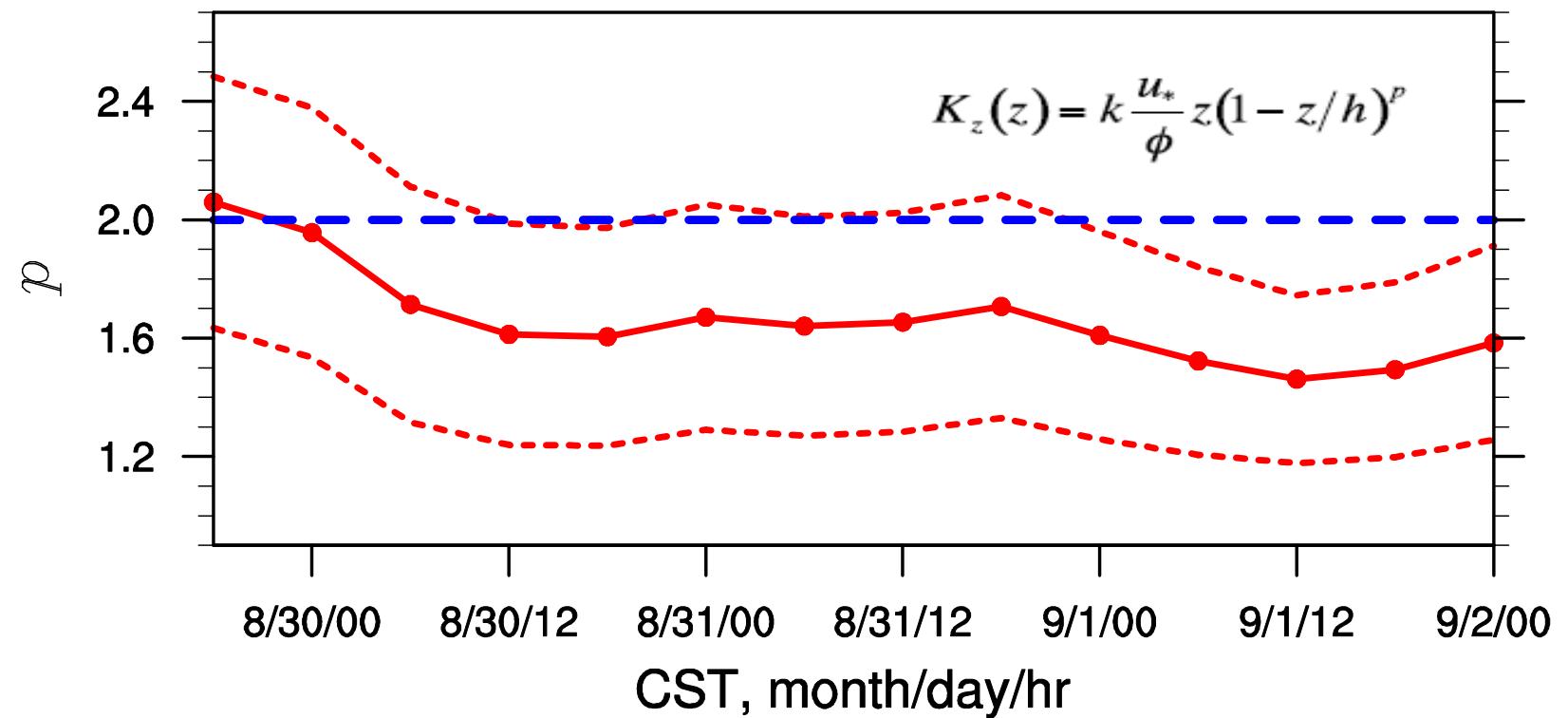
*0-72hr U, V, T & Q RMS forecast error over CONUS Jun 2003 (60 runs)*



(*Zhang et al. 2010; Zhang and Zhang 2011*)

# Simultaneous State and Parameter Estimation for Treatment of Model Error

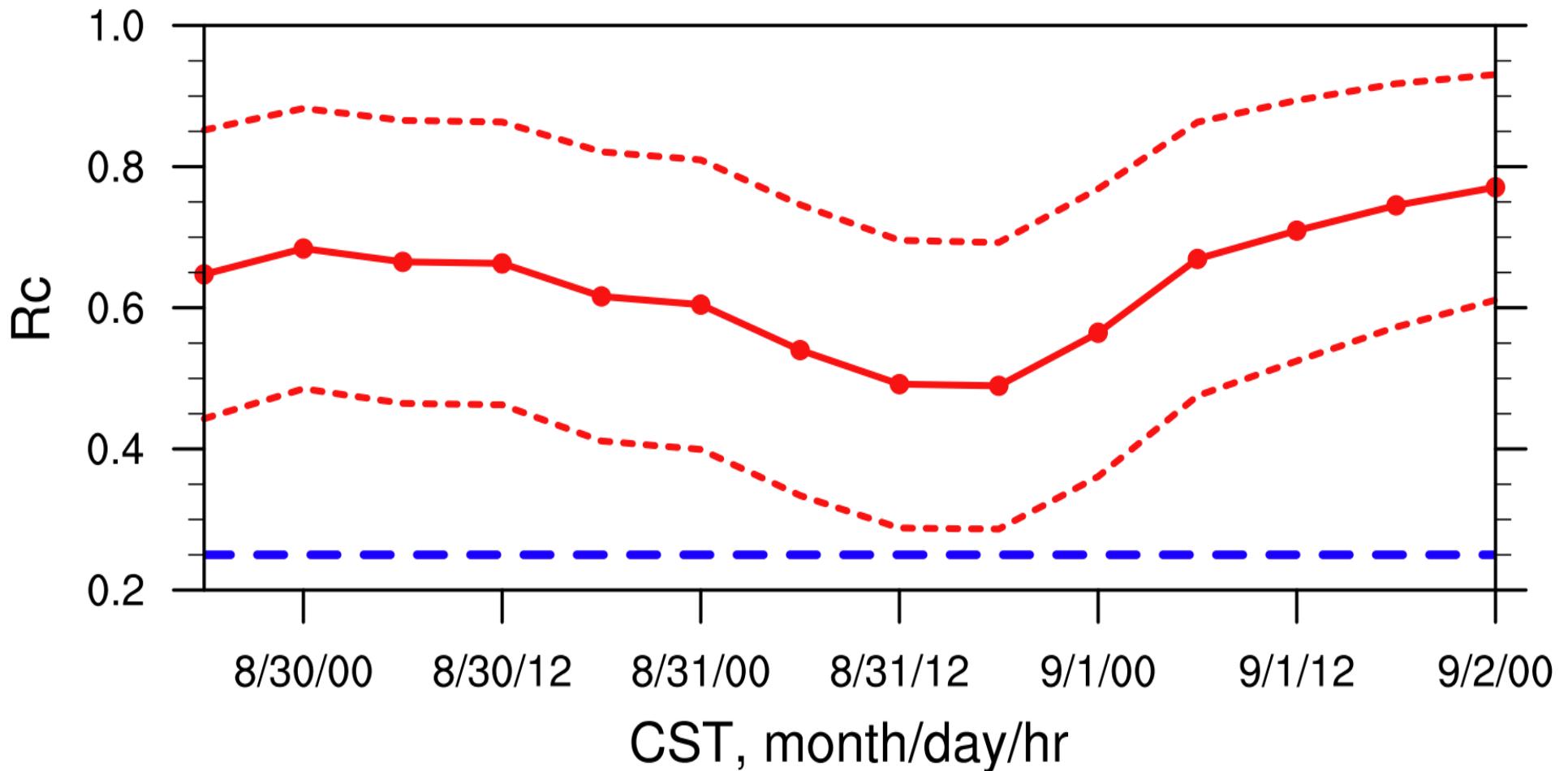
*A real-data study on WRF/PBL error*



During most of the simulation, SSPE predicts  $p$  values lower than 2.0 (default). This corresponds to stronger diffusivity in the middle and upper daytime PBL.

Hu, Zhang & Nielsen-Gammon (2010a GRL)

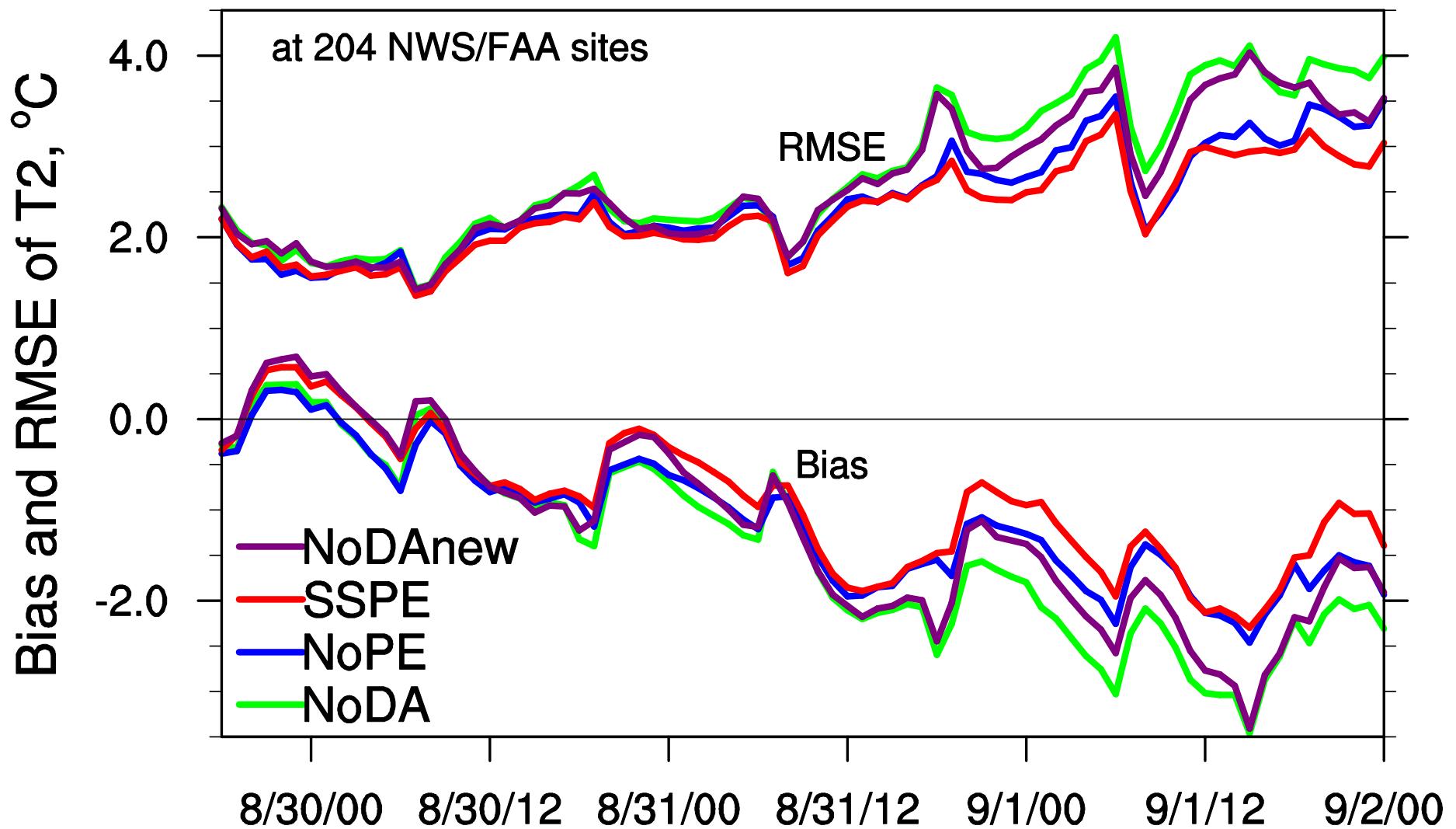
# Evolution of $R_c$



During the entire simulation, SSPE predicts  $R_c$  values higher than 0.25 (default). This corresponds to stronger mixing under weakly stable conditions.

Hu, Zhang & Nielsen-Gammon (2010a GRL)

# Bias and error of T2



# Concluding Remarks

- Storm-scale data assimilation with EnKF is certainly promising as in numerous studies from simple cloud to full NWP models, from OSSEs to real-data experiments with some success in real-time
- Inaccuracies in background error covariance sampling
  - ensemble size vs. accuracy vs. computational feasibility
  - covariance localization/inflation for multiscale problems
  - memory of initial ensemble sampling vs. feature lifespan
  - impacts of nonlinear, non-Gaussian statistics
- Errors in the forecast model and observation operator
  - model error: limited temporal and spatial resolutions and parameterization of subgrid-scale and stochastic processes
  - observation quantity, quality, error covariance, thinning and dimension reduction